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Thin Inductor for DC-to-DC Converter

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Abstract:

A thin inductor that measures 4 mm in thickness and features superimposed DC current and magnetic noise or low-leakage flux characteristics superior to those of conventional inductors has been developed. This was accomplished by combining twin ferrite cores of the closed magnetic path type originally designed by magnetic field analysis software with a fusion-bonded coil composed of fusion-insulated conductor wire winding. The thin inductor has been assembled with a circuit board of enhanced efficiency to fabricate a thin converter of thickness and volume less than half of those of conventional converters. Despite its smaller size, the thin converter has conversion efficiency, leakage flux, and heating characteristics superior to those of conventional converters.

1. Introduction

The decreasing size and weight of electronic equipment in recent years has resulted in their power supply circuit space being reduced. Considering the power supply circuit parts, the magnetic parts, radiator fins, and electrolytic capacitors account for decreasing proportions of the power supply circuit packaging space in that order. The magnetic parts are reported to be available in various structures adapted to the size and thickness reduction of specific power supply circuits according to the operating frequency and the amount of energy to be handled[1-4]. DC-DC converters in which an inductor with a winding on a drum-type Ni-Zn ferrite core is fixed to one side of a radiator and a hybrid IC circuit board is fixed to the other side of the radiator are used as general-purpose onboard DC-DC converters to locally stabilize power on the control boards of electronic equipment[5] (**Photo 1**).

The authors studied the size and thickness reduction of DC-DC converters (target thickness of 12.5 mm) and the magnetic

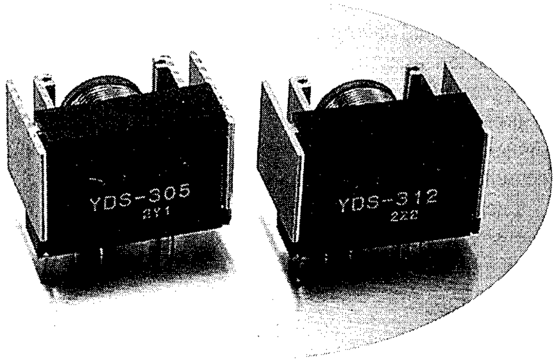

Photo 1 Conventional DC-DC converters with drum-type inductors (Courtesy of Yutaka Electric Mfg. Co., Ltd.)

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noise reduction of DC-DC converters to such a degree as to preclude adverse effects on other control parts on the basis of the following concepts:

(1)Replace a drum-type inductor that occupies about a half of the packing volume of a conventional DC-DC converter by a thin inductor of the closed magnetic path type.

(2)Review the circuit design of the conventional DC-DC converter, and reduce the size of radiator fins that account for the second largest percentage of the packing volume by increasing their efficiency.

2. Experimental Methods

2.1 Inductor design considerations

Drum-type inductors composed of Ni-Zn ferrites and used on conventional DC-DC converters are general-purpose magnetic parts used in various electronic circuits, because their core shape facilitates automation in the winding step. Also the high electrical insulation property of the Ni-Zn ferrite material allows the conductor wire to be directly wound on the core material resulting in lower inductor prices. In the DC-DC converter circuit the inductor plays a role as a filter that smoothes high-frequency pulsating voltage and current for voltage conversion with a capacitor and converts them into DC voltage and current. As its operating principle the inductor stores intermittent electrical energy as magnetic energy through its winding.

The drum-type core is structured to form magnetic dipoles of opposite polarity by itself to inhibit its own magnetization or to have a large demagnetization factor. For this reason the stored magnetic energy was small in size and was not conducive to the size reduction of parts. The magnetic flux generated by the core passes through air and forms a magnetic circuit. The resultant leakage flux exerts an adverse effect on adjacent electronic parts in such a way that they may malfunction. When built into electronic equipment, therefore, inductors called for special care to be exercised as to their arrangement.

The authors decided to design inductors according to the following considerations:

(1)Design an inductor shape as the closed magnetic path type to reduce leakage flux and as the thin type to facilitate installation in the converter replacing the conventional drum structure that is not conductive to the inductor size reduction.

(2)To accomplish the size reduction of the inductor, change from the Ni-Zn ferrite to the Mn-Zn ferrite that features superior permeability and saturation flux density as listed in **Table 1**.

(3)Determine the inductor dimensions in a single design attempt by using the magnetic field analysis software to complete the prototype design in a short period of time. The software was originally developed by Ceramics & Metals Lab. at the Advanced Technology Research Laboratories of Nippon Steel.

The magnetic field analysis software is based on a three-dimensional finite element method. It is characteristic in that it uses the edge element method suited for high-speed computing, instead of the nodal element method in widespread use[6]. It can calculate the superimposed DC current as the inductance value required for converter design[7]. The nodal element method is a finite element method that performs computation by placing unknown variables at the nodes of discretized elements. The edge element method assigns unknown variables to the edges of elements. It can express the continuity of physical quantities between the elements more accurately than the nodal element method. Since the matrix to be finally solved by the edge element method thus becomes a principal diagonal dominant matrix, the edge element method is characterized by the high speed of matrix computation itself. The solutions obtained by the magnetic field finite element method are usually magnetic flux density and magnetic field strength. The design of an inductor calls for the computation of the inductance value on which the DC current is superimposed (superimposed DC current characteristic value) as required for circuit design.

Table 1 Soft oxide-based magnetic materials

Material	Relative permeability μ_r (at 100 kHz)	Saturation magnetic flux density B_s (mT)	Resistivity ρ (Ωcm)
Mn-Zn ferrite	2,300	400-500	1-10
Ni-Zn ferrite	1,600	300-400	10^4

The authors devised the method of entering as a physical quantity for the finite element method the incremental permeability correlated with the superimposed DC current value and calculating the inductance from the calculated magnetic flux density and magnetic field strength. In addition to the edge element method, the three-dimensional magnetic field analysis software required for the design of inductors was thus completed.

The inductance value of the inductor is proportional to the square of the number of turns. How to construct the winding is key to obtaining a high inductance value with a small size. A winding structure using fusion-insulated conductor wire was considered advantageous over conventional conductor wire in terms of miniaturization. The winding structure and a printed coil were devised and compared. The fusion-insulated conductor wire is used in motor windings and similar applications. The conductor wire is coated first with an insulation layer and then with a fusion layer. When the winding is given post-heat treatment, the insulation and fusion layers are melted together to form an integral coil, requiring no bobbin. The printed coil has copper plates photo-etched on a printed board to form a winding pattern.

These computational and experimental results led to the trial fabrication of an inductor with the target thickness of 4 mm and with superimposed DC current and magnetic noise (leakage flux) characteristics superior to those of the conventional drum-type inductor. The superimposed DC current and magnetic noise characteristics of the thin inductor were compared with those of the conventional drum-type inductor. The superimposed DC current characteristics were measured with LCR meters (Hewlett-Packard Japan Models 4284A and 4284A1) by superimposing direct currents of 0 to 1.6 A on sine wave alternating currents at a frequency of 50 kHz and amplitude of 1 mA. The leakage flux was measured with a gauss meter (Denshi Denji Kogyo Model GM-1120).

2.2 Characteristic evaluation of DC-DC converter equipped with thin inductor

A DC-DC converter with a maximum output current of 1.0 A was test-made by attaching a prototype inductor and a circuit board of enhanced efficiency to the respective surfaces of a radiator. The circuit is a noninsulated power supply of the self-excited step-down chopper type to step down the DC input voltage. The thin inductor was then compared with the conventional drum-type inductor in efficiency, output noise, and heating characteristics. The surface temperature of each part was measured with a thermocouple after thermal saturation, and the temperature difference or temperature rise ΔT from the ambient temperature was determined.

3. Experimental Results and Discussion

3.1 Core shape of thin inductor

The construction of the prototype thin inductor is shown in **Fig. 1**. A fusion-insulated conductor wire wound and bonded to a coil or a printed coil is sandwiched between type ER and I (plate-like) flat Mn-Zn ferrite cores.

The combination of the type ER and I ferrite cores measures 17-mm long, 13-mm wide, and 4-mm thick. The volume and thickness were made smaller than those of a conventional drum-type inductor that has the same superimposed DC current and measures 18 mm in diameter and 14 mm in thick.

The mesh and magnetic flux density distribution used for analysis by the magnetic field analysis software are shown in **Fig. 2**. In the design with the magnetic field analysis software, care was exercised to prevent the formation of localized portions of high magnetic flux density. For localized portions of high magnetic flux density increase core loss and form heat spots. The top and bottom ferrite cores are 1.5 mm in total thickness, the winding space is 1 mm, and the central projection center gap is 0.2 mm. In principle the core height can be reduced further by reducing the core thickness. Given the brittleness of the ferrite, the core thickness cannot be made so much. Reducing the core thickness reduces the cross-sectional magnetic parch area of the core. The plan-view size of the core must be increased to compensate for this reduction in the cross-sectional area. For this reason, the optimum thickness was put at 1.5 mm.

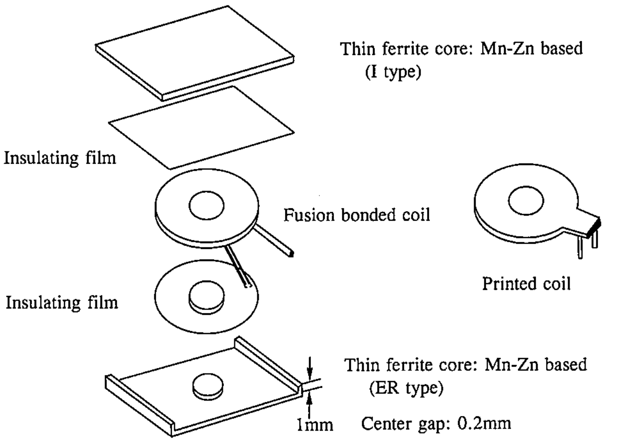

Fig. 1 Construction of thin inductor

3.2 Trial fabrication of inductor winding

The prototype winding is described next.

The fusion-insulated ribbon conductor wire is a two-layer covered conductor wire that has a fusion coating baked on a flat, 0.8-mm wide and 0.07-mm thick covered conductor wire. The ribbon conductor wire was wound on a bobbin by 26 turns and bonded by heating with hot air, and the formed coil was then removed from the bobbin. The flat ribbon conductor wire can be wound tighter to the flat ferrite core of the same cross-sectional area than a round conductor wire. The number of turns can be thus increased to obtain a higher inductance value. The combination of the winding with Mn-Zn ferrite cores cannot provide high enough electrical insulation, however. A 100-μm thick insulating film was inserted between the fusion-bonded coil and flat ferrite core to successfully pass the 500 VDC withstand voltage test specified for converter parts.

A double-sided copper-clad flexible printed wiring board was photo-etched to form a spiral, flat coil, measuring 0.8-mm wide and 0.07-mm thick. Six coil layers of three turns each were produced through insulator layers, or 18 coil turns were laminated in total. The flat coils were electrically connected in series by copper plating through holes so that current would flow in the same direction in each flat coil. The laminated structure was coated with insulating material on both surfaces.

3.3 Characteristic evaluation of prototype inductors

The superimposed DC current characteristics of the inductors are comparatively shown in **Fig. 3**. The thin inductor with the fusion-bonded coil produced higher inductance than the thin inductor with the printed coil. This was advantageous in reducing the ripple voltage of DC-DC converters. The difference in the inductance value is due to the difference in the number of conductor

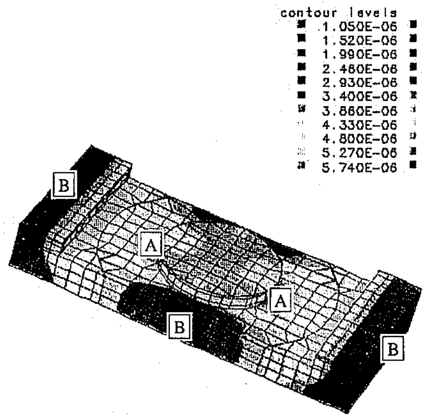

Fig. 2 Mesh and magnetic flux density distribution of thin inductor (magnetic flux density is highest in portions A and lowest in portions B)

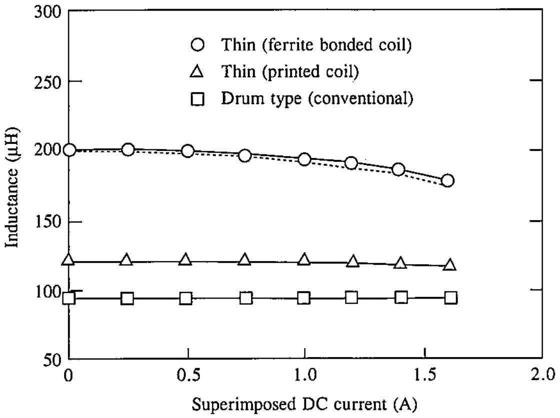

Fig. 3 Superimposed DC current of thin and conventional drum-type inductors (calculated values indicated by dotted line)

wire turns. With the printed coil the conductor wire layer thickness is the same as the flexible printed wiring board insulating film thickness of about 75 µm. This thickness was reduced to about 20 µm for the fusion-bonded coil, because the copper conductor wire was wound more tightly. The conventional drum-type inductor has a 0.7-mm round copper wire wound in 37 turns. Since this structure has a large demagnetization factor, the inductance value is small.

The values calculated by the magnetic field analysis software are indicated by the dotted line. The calculated values agree well with the measured values. This means that the computational tool was effective in predicting the superimposed DC current characteristics of the inductors.

The leakage flux of the new and conventional inductors is discussed next.

The leakage flux of the thin inductors is shown as compared with the conventional drum-type inductor in **Fig. 4**. With a DC current of 1 A applied to the coil, the leakage flux was measured in relation to the distance from the top of the through hole for the conventional drum-type inductor and from the ferrite core surface above the central projection for the thin inductor. Since the flux formed a closed loop in the ferrite core, the leakage flux from the thin inductors was about one-tenth of that for the drum-type inductor. The leakage flux is slightly smaller with the printed coil than with the fusion-bonded coil, because the smaller number of turns in the printed coil reduces the existing magnetic field itself. The leakage flux was measured at distances corresponding to the thicknesses of 14 and 4 mm for the conventional drum-type inductor and the thin inductor, respectively. When the thin inductor is compared with the drum-type inductor in the leakage flux from the bottom of the ferrite core, its leakage flux reduction will more conspicuously appear.

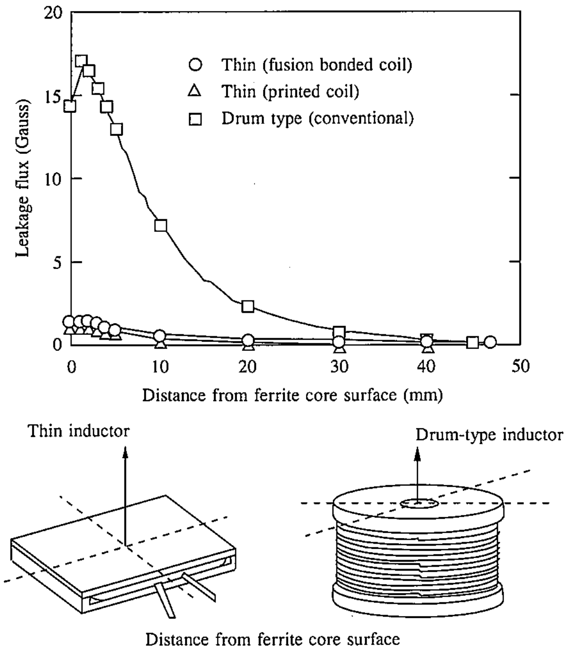

Fig. 4 Magnetic noise of thin and conventional drum-type inductors (with application of DC current of 1 A)

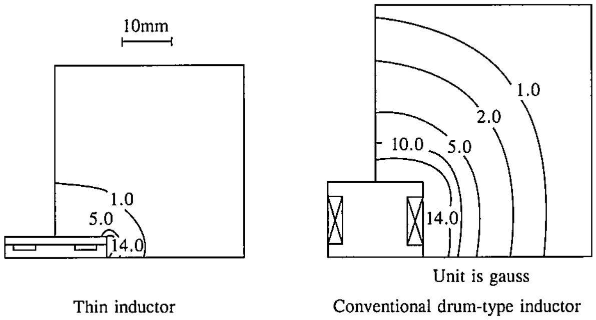

Fig. 5 Magnetic field analysis results of leakage flux of thin inductor and conventional drum-type inductor

The leakage flux of the thin and drum-type inductors calculated by the magnetic field analysis software is shown in **Fig. 5**. The leakage flux from the thin inductor is clearly smaller than that from the conventional drum-type inductor as indicated by the measured values. This finding confirms the effectiveness of the magnetic field analysis software in predicting the leakage flux of magnetic parts and designing magnetic parts with low magnetic noise. The reduction in leakage flux is advantageous for the miniaturization of electronic equipment because it prevents the malfunction of IC parts and circuits and allows the high-density packaging of electronic parts.

3.4 Installation of thin inductor in DC-DC converter and comparison of thin converters with conventional converter

The construction and appearance of prototype DC-DC converters fitted with thin inductors are shown in **Fig. 6** and **Photo 2**, respectively. The thin inductor is attached to one side of the fixing member, and the circuit board and radiator are attached to the other side of the fixing member. As shown in **Table 2**, the thickness and volume of the prototype thin converters are both less than half of those of the conventional DC-DC converter.

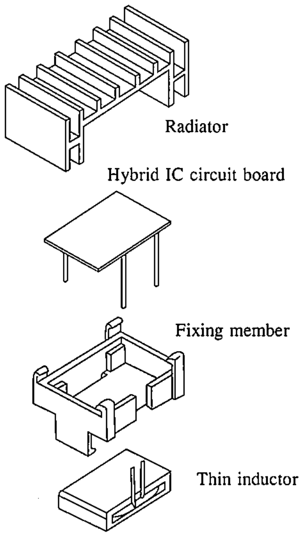

Fig. 6 Construction of prototype thin converter

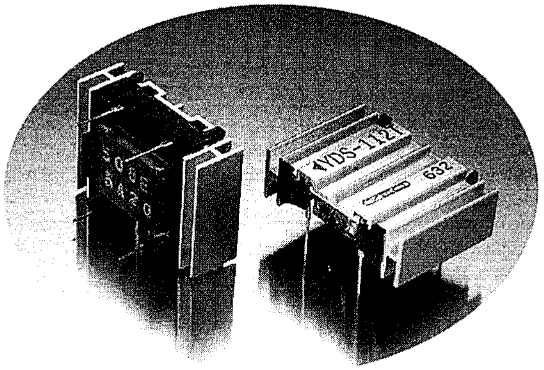

Photo 2 General view of prototype thin converters (Courtesy of Yutaka Electric Mfg. Co., Ltd.)

Table 2 Dimensions of prototype and conventional converters

	Dimensions (length×width×thickness) (mm)	Volume (mm³)
Prototype converter	32×23×12.2	8,979.2
Conventional converter	28×27.5×26	20,020.0

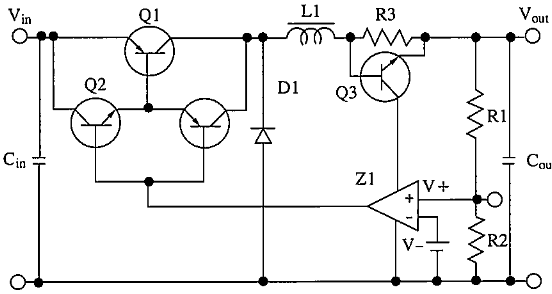

Fig. 7 Equivalent circuit of prototype thin converter (C_{in} and C_{out} are external parts)

The circuit is that of a regulator of the self-excited step-down chopper type. Its equivalent circuit is illustrated in **Fig. 7**. The operating principle is briefly described. When the output voltage V_+ which is divided by the resistors R1 and R2 is lower than the minus input V_- of the comparator Z1, the output of Z1 goes low, the main switching device Q1 turns on with the emitter and base biased in the forward direction. The output voltage passes through the LC filter composed of L1 and C_{out} and rises further. When V_+ goes higher than V_-, the output of Z1 goes high, and Q1 turns off. The energy stored in L1 when Q1 was turned on is released to the load side through the flywheel diode D1, and the output voltage gradually drops. The above series of operations is repeated to stabilize the output voltage. Being of the self-excited type, the prototype thin converter has no oscillators, and the oscillation frequency is self-controlled by the input voltage and output power. The circuit formed by R3 and Q3 is an overcorrect protector for the output current.

The prototype thin converter circuit differs from the conventional DC-DC converter circuit in that the resistor inserted between the base and emitter of the main switching device Q1 composed of a pnp-type semiconductor is replaced by the small off switching device Q2 composed of an npn semiconductor. The turn-off time of the main switch is thus advanced to reduce the circuit inside loss and improve the conversion efficiency.

When a bipolar transistor is in the on state, minority carriers are stored in the base and emitter regions. When the base current becomes zero, the time is required to discharge the stored charge until the bipolar transistor turns off. In the conventional DC-DC converter circuit, the main switching device Q1 turns off only with the reverse bias voltage applied by the resistor between the base and emitter. The turn-off time of Q1 thus depends on the natural disappearance time of the charge stored between the base and emitter when Q1 was turned on. The timing of Q1 turning off is delayed, and the switching loss that is the product of the switch voltage and current the instant Q1 turns off is large.

In the prototype thin converter circuit, a bipolar transistor composed of an npn semiconductor replaces the resistor between the base and emitter of the main switch Q1 composed of a pnp semiconductor and acts as the off switching device Q2. The instant Q1 turns off, Q2 turns on to forcibly remove the stored charge, shortening the turn-off time of Q1 and increasing the conversion efficiency.

The prototype DC-DC converter operates at an input voltage of 10 to 40 V and output voltage of 5 or 12 V (the difference between the input and output voltages is greater than 4 V). The conversion efficiency and ripple voltage of the prototype thin DC-DC converter when operated at an input voltage of 24 V and output voltage of 12 V are shown as compared with those of a conventional DC-DC converter in **Fig. 8**. As compared with the conventional converter, the conversion efficiency is improved, and the ripple voltage is reduced. The reduction in the ripple voltage is attributable to the increase in the inductance of the thin inductor.

Fig. 9 shows the output voltage waveforms of the thin DC-DC converter after thermal saturation and switching, respectively, when the output current was 1.0 A. The oscillation frequency was about 50 kHz.

The temperature rise ΔT of each part in the thin DC-DC converter after thermal saturation when the output current was 1.0 A

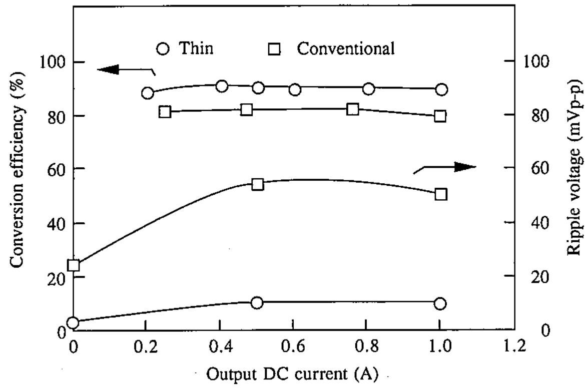

Fig. 8 Electrical properties of thin and conventional converters (input voltage of 24 V and output voltage of 12 V)

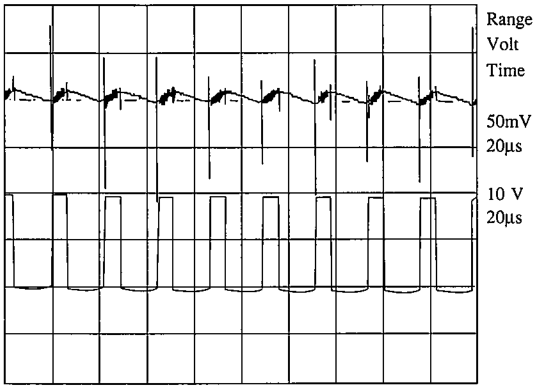

Fig. 9 Output voltage waveforms of thin DC-DC converter after thermal saturation and switching (input voltage of 24 V, output voltage of 12 V, and output current of 1.0 A)

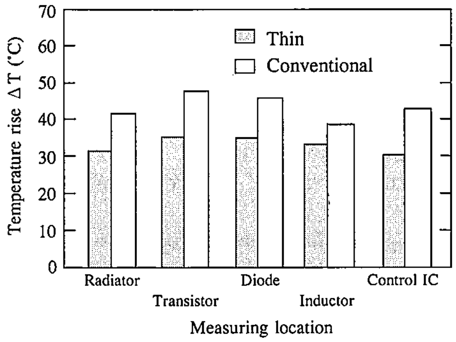

Fig. 10 Heating characteristics of thin and conventional DC-DC converters

is shown as compared with that of the conventional DC-DC converter in **Fig. 10**. Despite the fact that the thin converter is smaller than a half of the conventional converter, its temperature rise is less than that of the conventional converter.

4. Conclusions

A new thin DC-DC converter has been successfully developed with its thickness and volume more than 50% smaller than those of a conventional onboard DC-DC converter fitted with a drum-type inductor. Despite its smaller size, the thin DC-DC converter has electrical properties (conversion efficiency and ripple voltage), heating characteristics, and magnetic noise (leakage flux) superior to those of the conventional DC-DC converter. There are the following three main development points:

(1)A 4-mm thick inductor with better superimposed DC current and magnetic noise properties than those of a conventional drum-type inductor was successfully designed by making the most of originally developed magnetic field analysis software.

(2)A flat fusion-insulated conductor wire was wound and bonded to form a fusion-bonded coil. The fusion-bonded coil was installed in the narrow 1-mm space between the flat ferrite cores to provide a high inductance value.

(3)As compared with a conventional DC-DC converter circuit, a small switching device was inserted between the base and emitter of the main switching device. The small switching device rapidly removed the stored charge of the main switch to reduce the loss of the main switch. As a result, the conversion efficiency was enhanced, and the radiator was reduced in size.

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